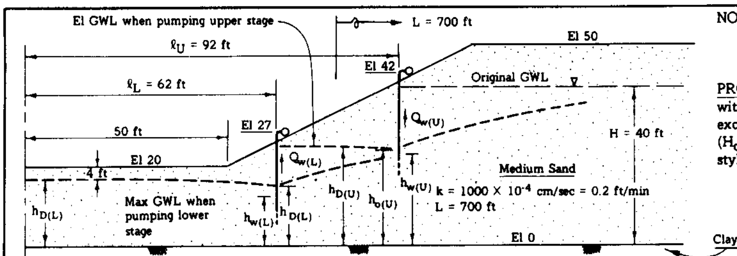
APPENDIX D

EXAMPLES OF DESIGN OF DEWATERING AND PRESSURE RELIEF SYSTEMS

This appendix consists of figures D-1 through D-10, which follow.



NOTES:
1. System symmetrical about ℄.
2. Bottom of excavation equals 100 × 750 ft.
3. Clay is impervious and not under artesian pressure.
4. Line source of seepage.

PROBLEM: Determine spacing of 2-1/2-in. self-jetting wellpoints with 2-in.-diam riser pipes to lower GWL 4 ft below bottom of excavation, assuming vacuum (v) = 24 ft, head loss in collector (H_c) = 2 ft, and intake of pump is 2 ft above collector. Assume style D, Mesh E, wellpoints are to be used.

SOLUTION: Compute spacing of wellpoints so that available (net) vacuum in headers (20 ft) will lower water level at wellpoints below that required to produce the necessary h_D. Assume two stages of wellpoints will be required and that each stage will be installed 2 ft above the groundwater table existing at the time of installation. Also, assume $r_w = 0.12$ ft.

Upper stage. Install upper stage at el 42, and 92 ft from ℄ of the excavation, to temporarily lower the groundwater 15 ft to el 25 to permit installation of a lower stage of wellpoints at el 27. Required $h_D = 25$ ft. Compute h_o at a partially penetrating slot from eq 4 (fig. 4-3)

$$h_{D(U)} = h_{o(U)}\left[\frac{1.48}{L}(H - h_o) + 1\right] \quad \therefore \quad 25 = h_{o(U)}\left[\frac{1.48}{700}(40 - h_o) + 1\right] \quad \therefore \quad h_{o(U)} = 24.2 \text{ ft}$$

Compute Q_p to a partially penetrating slot from eq 3 (fig. 4-3).

$$Q_p = \left[0.73 + 0.27\left(\frac{H - h_o}{H}\right)\right]\frac{k}{2L}\left(H^2 - h_o^2\right) = \left[0.73 + 0.27\left(\frac{40 - 24.2}{40}\right)\right]\frac{0.2}{2(700)}(40^2 - 24.2^2)$$

$$Q_p = 0.121 \text{ cfm/ft} = 0.91 \text{ gpm/ft}$$

Assume $a = 10$ ft, then $Q_w = aQ_p = 9.1$ gpm.

From a plan flow net it can be shown that the average flow for a finite line of wellpoints for this excavation will be about 35 percent greater than for an infinite line. Thus $Q_w = 1.35$ (9.1 gpm) = 1.64 cfm.

Calculate head at wellpoint, h_w, from eq 1 (fig. 4-22).

$$h_D^2 - h_w^2 = \frac{Q_w}{\pi k}\ln\frac{a}{2\pi r_w} \quad \therefore \quad h_w^2 = (25)^2 - \frac{1.64}{0.2\pi}\ln\frac{10}{2\pi(0.12)} \quad \therefore \quad h_w = 24.9 \text{ ft}$$

For $Q_w = 12.3$ gpm and well screen length = 3 ft, the hydraulic head losses are as follows:

$H_e = 0.2$ ft from fig. 46a, curve 7 $\quad$ $H_s = 0.9$ ft from fig. 46b $\quad$ $H_r + H_v = 0.5$ ft from fig. 4-26c which includes loss in swing.

$H_{w(U)} = 1.6$ ft. Thus $h_{w(U)} - H_{w(U)} = 24.9 - 1.6 = 23.3$ ft.

Therefore, the required effective vacuum in the header = el 42 - 23.3 = 18.7 ft. Since this value is slightly less than the available 20 ft, a wellpoint spacing of 10 ft with header at el 42 and top of wellpoint at el 21 would be satisfactory.

Lower stage. Install lower stage at el 27 and 62 ft from ℄ of the excavation, to lower the groundwater to el 16. Required $h_{D(L)} = 16$ ft. Compute $h_{o(L)}$ at a partially penetrating slot from eq 4 (fig. 4-3).

$$h_{D(L)} = h_{o(L)}\left[\frac{1.48}{L}(H - h_o) + 1\right] \quad \therefore \quad 16 = h_{o(L)}\left[\frac{1.48}{700}(40 - h_o) + 1\right] \quad \therefore \quad h_{o(L)} = 15.2 \text{ ft}$$

Compute Q_p to a partially penetrating slot from eq 3 (fig. 4-3).

$$Q_p = \left[0.73 + 0.27\left(\frac{H - h_{o(L)}}{H}\right)\right]\frac{k}{2L}\left(H^2 - h_o^2\right) = \left[0.73 + 0.27\left(\frac{40 - 15.2}{40}\right)\right]\frac{0.2}{2(700)}(40^2 - 15.2^2) = 0.175 \text{ cfm/ft} = 1.3 \text{ gpm/ft}$$

Assume $a = 15$ ft, then $Q_w = aQ_p = 15 \times 1.3 = 19.5$ gpm for an infinite line of wellpoints. For finite line of wellpoints, increase Q_w in this case by 35 percent. $Q_w = 1.35 \times 26.3$ gpm = 3.52 cfm.

Calculate head at wellpoint, $h_{w(L)}$, from eq 1 (fig. 4-22).

$$h_{D(L)}^2 - h_{w(L)}^2 = \frac{Q_w}{\pi k}\ln\frac{a}{2\pi r_w} \quad \therefore \quad h_{w(L)}^2 = (16)^2 - \frac{3.52}{0.2\pi}\ln\frac{15}{2\pi(0.12)} \quad \therefore \quad h_{w(L)} = 15.5 \text{ ft}$$

For $Q_w = 26.3$ gpm and a well screen length of 3 ft, the hydraulic head losses are as follows:

$H_e = 0.3$ ft from fig. 4-25a $\quad$ $H_s = 2.0$ ft from fig. 4-25b $\quad$ $H_r + H_v = 1.5$ ft from fig. 4-25c

$H_{w(L)} = 3.8$ ft. Thus $h_w - H_w = 15.5 - 3.8 = 11.7$ ft.

Therefore, the required effective vacuum in the header = el 27 - 11.7 = 15.3 ft. Since the vacuum available in the header is 20 ft, the assumed spacing would be satisfactory.

The wellpoints would be installed with 21-ft-long riser pipes.

It would be advisable to observe groundwater levels before and during pumping of the upper stage and to measure the discharge. From these data, the design of the lower stage could be adjusted if observed values were appreciably different from the design values. Such differences can occur because of limitations in the accuracy of k, L, and H_w used in design.

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Figure D-1. Open excavation; two-stage wellpoint system; gravity flow.

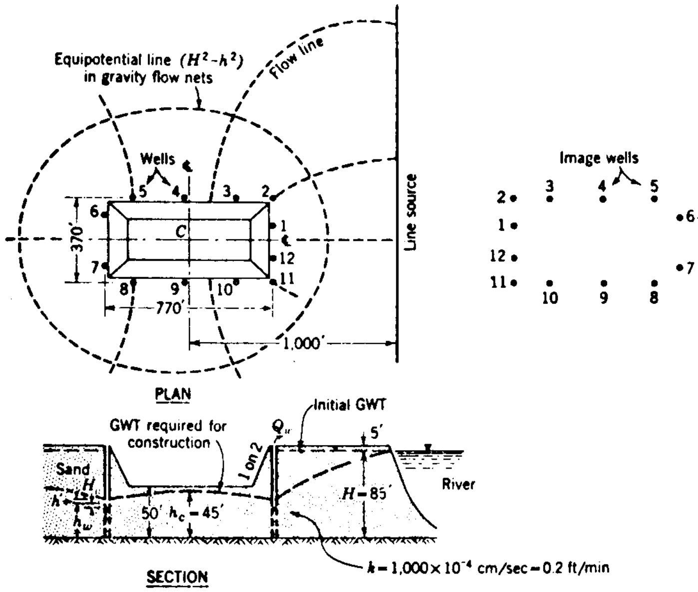
PROBLEM: Design a system of 16-in. slotted screen wells, pumped by deep-well turbine pumps, for lowering the groundwater level 5 ft below the bottom of the excavation. Assume maximum allowable Q_w = 1,200 gpm, wells located 5 ft from top of slope, well radius r_w = 1 ft, and D_{10} of gravel filter = 0.25 mm.

SOLUTION: Estimate total flow required from eq 3(fig. 4-17) using radius A_e of an equivalent large-diameter well computed from eq 6 (fig. 4-14).

$$A_e = \frac{4}{\pi}\sqrt{770/2 \times 370/2} = 340 \text{ ft}$$

$$Q_T = \frac{\pi(0.2)(85^2 - 45^2)}{\ln[(2 \times 1{,}000)/340]} = 1{,}840 \text{ cfm} = 13{,}800 \text{ gpm}$$

Use 12 wells with Q_w = 1,150 gpm. Locate wells as shown in plan so as to intercept equal quantity of flow as indicated by flow net and to obtain approximate level drawdown beneath excavation. Compute head h_e at center of excavation and head h_w at a well from eq 3 and 4 (fig. 4-18) to check adequacy of system.



Head at Point C and Well 4 Computed by Method of Images for Q_w = 1,150 gpm = 153 cfm

Well	Head at Point C: S_i ft	r_i ft	$\ln \frac{S_i}{r_i}$	Head at Well 4: $S_{i,4}$ ft	$r_{i,4}$ ft	$\ln \frac{S_{i,4}}{r_{i,4}}$
1	1,620	390	1.42	1,650	410	1.39
2	1,630	420	1.36	1,640	400	1.41
3	1,800	290	1.82	1,800	240	2.02
4	2,040	180	2.42	2,050	1	7.63
5	2,280	330	1.93	2,300	250	2.22
6	2,400	390	1.82	2,420	370	1.88
7	2,400	390	1.82	2,435	460	1.67
8	2,280	330	1.93	2,330	440	1.67
9	2,040	180	2.42	2,090	370	1.73
10	1,800	290	1.82	1,840	435	1.44
11	1,630	420	1.36	1,675	540	1.13
12	1,620	390	1.42	1,650	480	1.24

$F'_c = 21.54 \times 154 = 3320$ $\quad$ $F'_w = 25.44 \times 154 = 3920$

From eq 2 and 3 (fig. 4-18), $H^2 - h_c^2 = \frac{3320}{\pi(0.2)} = 5280$. From eq 3 and 4 (fig. 4-18), $H^2 - h_w^2 = \frac{3920}{\pi(0.2)} = 6240$

$h_c = \sqrt{85^2 - 5280} = 44.1$ ft $\quad$ $h_w = \sqrt{85^2 - 6240} = 31.4$ ft

The corresponding flow per foot of well screen is 1,150/32, or 36 gpm per ft. Compute head loss in well H_w from fig. 4-24.

$H_e = 1.80$ ft (from fig. 4-24a) $\quad$ $H_v = 0.06$ ft (from fig. 4-24c)

$H_r + H_s = 0.15\left(\frac{32}{100} \times \frac{1}{2}\right) = 0.02$ (from fig. 4-24b and using the flow through one-half the length of screen)

$H_w = 1.88$ ft, say 2.0 ft

Thus $h_w - H_w = 32.0 - 2.0 = 30.0$ ft. Bowls of pump should be set about 2 ft below this level, and the pump provided with a 10-ft suction pipe. With such a suction pipe, $H_r + H_s$ will be slightly less than the value computed above. Had the approximate method in fig. 4-19 (array 4) been used, the following values of F'_c and F'_w would have been obtained:

$$F'_c = 154 \times 12 \ln \frac{2 \times 1{,}000}{340} = 3270$$

$$F'_w = 154 \times \left[12 \ln\left(\frac{2 \times 1{,}025}{340}\right) + \ln \frac{340}{12 \times 1}\right] = 3840$$

These values agree closely with those computed by the exact method.

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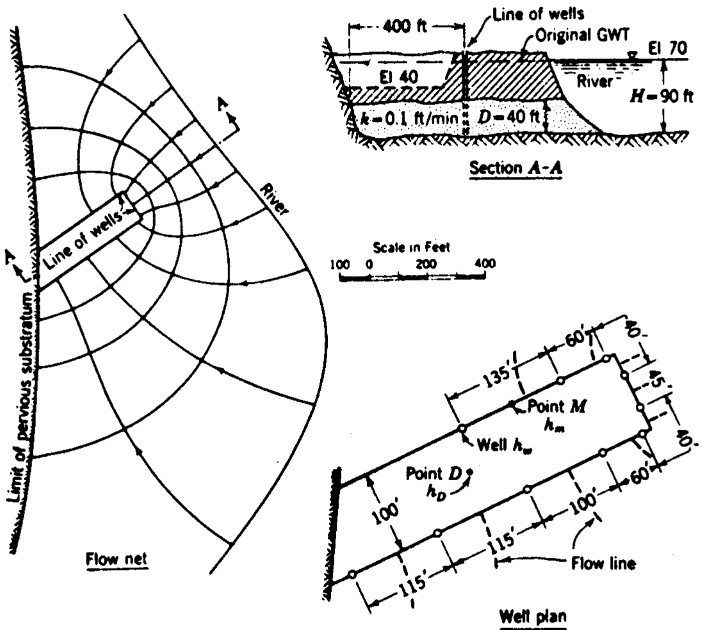
Figure D-2. Open excavation; deep wells; gravity flow.



PROBLEM: Given the flow net, the data in the figure, and the plan of wells as shown, compute the well flow required to reduce the head in the sand stratum to el 40 ft at point D, the corresponding head h_w at the wells, h_m midway between wells, and h_D at the center of the excavation. Assume that wells fully penetrate the pervious stratum and that $D = 40$ ft, $k = 500 \times 10^{-4}$ cm/sec = 0.1 fpm, and $r_w = 1.0$ ft.

SOLUTION: Flow to slot (or wells) from flow net, eq 5 (fig. 4-27)

$$Q_T = k(H - h_e)\frac{N_f}{N_e} D = 0.1(90 - 60)\ \frac{10.0}{4.0} \times 40 = 300 \text{ cfm} = 2{,}250 \text{ gpm}$$

Assume 10 wells located as shown in "Well Plan." Since a well has been spaced at the center of each flow channel, the flow per well is the same for all wells. Thus Q_w = 225 gpm or 30 cfm per well.

From eq 2 (fig. 4-28)

$$H - h_w = \frac{30}{0.1(40)}\left[10\left(\frac{4}{10}\right) + \frac{1}{2\pi}\ \ln\frac{90}{2\pi(1)}\right] = 33.2 \text{ ft}$$

Since the average well spacing a is approximately 90 ft, compute Δh_m from eq 3 (fig. 4-2a) for $a = 90$ ft.

$$\Delta h_m = \frac{30}{2\pi(0.1)40}\ \ln\frac{90}{\pi(1)} = 4.0 \text{ ft}$$

Thus

$$H - h_m = H - h_w - \Delta h_m = 33.2 - 4.0 = 29.2 \text{ ft}$$

From eq 1 (fig. 4-2a) for $a = 90$ ft,

$$\Delta h_D = \Delta h_w = \frac{30}{2\pi(0.1)40}\ \ln\frac{90}{2\pi(1)} = 3.2 \text{ ft}$$

Thus

$$H - h_D = H - h_w - \Delta h_D = 33.2 - 3.2 = 30.0 \text{ ft}$$

The heads h_w, h_m, and h_D in terms of elevation are as follows:

$$h_w = 70 - 33.2 = 36.8 \text{ ft MSL}$$

$$h_m = 70 - 29.2 = 40.8 \text{ ft MSL}$$

$$h_D = 70 - 30.0 = 40.0 \text{ ft MSL}$$

Since GWT is to be lowered to el 40 at point D and since the computed head at this point is at el 40.0, Q_w = 30 cfm, or 225 gpm per well will produce the required head reduction. The values of Δh_D, Δh_m, and $(H - h_w)$ also can be computed from eq 1 and 3 (fig. 4-21) and 3 (fig. 4-28) respectively, as shown below. Note that the values so obtained are identical to those computed above.

From fig. 4-21 $\theta_a = 0.42$ and $\theta_m = 0.53$ for $a/r_w = 90$ and $W/D = 100$ percent.

From eq 3 (fig. 4-28)

$$H - h_w = \frac{30}{0.1(40)}\left[10\left(\frac{4}{10}\right) + 0.42\right] = 33.2 \text{ ft}$$

From eq 3 (fig. 4-21)

$$\Delta h_m = \frac{30(0.53)}{0.1(40)} = 4.0 \text{ ft}$$

From eq 1 (fig. 4-21)

$$\Delta h_D = \Delta h_w = \frac{30(0.42)}{0.1(40)} = 3.2 \text{ ft}$$

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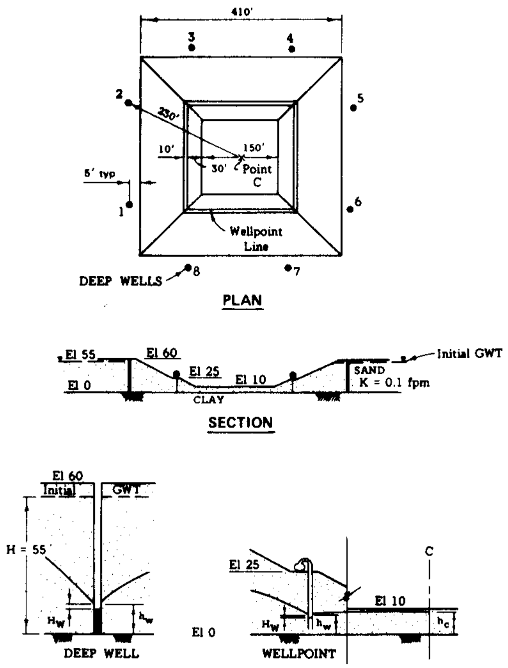
Figure D-3. Open excavation; artesian flow; pressure relief design by flow net.



Design of a combined deep-well and well and wellpoint system for dewatering a slope

PROBLEM: Design a combined deep-well and wellpoint system to lower the groundwater to 2 ft below the bottom of the excavation. Use deep wells located 5 ft back of the edge of the excavation to lower the groundwater to permit the installation of a single stage of wellpoints for lowering the groundwater below the bottom of the excavation.

SOLUTION:

Deep wells. The deep-well system must be designed such that the groundwater level is lowered 2 ft below the elevation at which the header pipes for the wellpoint system will be set. Set header pipes for wellpoint system at el 25. Required drawdown:

$$H - h_c = 55 - 23 = 32 \text{ ft}$$

Locate fully penetrating wells in a circular array around the perimeter of the excavation, A_e = 230 ft . Estimate radius of influence, R , from fig. 4-23 For k = 0.1 fpm and final drawdown, $H - h_D$ = 55 - (10 - 2) = 47 ft, R = 3180 ft.

Calculate flow to well system from eq 3 (fig. 4-13) and 2 (fig. 4-14).

$$H^2 - h_c^2 = \frac{nQ_w \ln R/A_e}{\pi k}$$

$$(55)^2 - (23)^2 = \frac{nQ_w \ln 3180/230}{\pi 0.1}$$

$$nQ_w = 299 \text{ cfm} = 2233 \text{ gpm}$$

Try eight wells with radius, r_w = 1.0 ft (12-in. screen with 6-in. filter).

$$Q_w = \frac{299}{n} = \frac{299}{8} = 37.4 \text{ cfm} = 280 \text{ gpm}$$

Calculate drawdown at well from eq 3 (fig. 4-13) and 1 (fig. 4-14)

$$H^2 - h_w^2 = \frac{Q_w}{\pi k} \ln \left(\frac{R^n}{nr_w\ A_e^{(n-1)}}\right) = \frac{Q_w}{\pi k}[n \ \ln R - \ln nr_w - (n-1) \ln A_e]$$

$$(55)^2 - h_w^2 = \frac{37.4}{\pi(0.1)}[8 \ln 3180 - \ln 8(1.0) - (8 - 1) \ln 230]$$

$$h_w = 11.1 \text{ ft}$$

Wells should have about 15 ft of 12-in. well screen. From fig. 4-24, estimate H_w = 0.9 ft : $h_w - H_w$ = 11.1 - 0.9 = 10.2 ft.

Wellpoints. Use 3-ft slotted wellpoints with filter, r_w = 0.5 ft, and 2-in. riser pipes 21 ft long; set header pipe at el 25. Assume wellpoint pump vacuum equals 24 ft with 2-ft friction loss in header and pump suction set 2 ft above header pipe. Net vacuum in header pipe equals 20 ft. Install wellpoints 110 ft from ℄ ; from eq 6 (fig. 4-14). A_e = 140 ft.

Assume some head, h , at the line of wells; the flow to the combined system can be expressed as follows (eq 3 (fig. 4-13) and 2 (fig. 4-14).

$$H^2 - h^2 = \frac{nQ_w + Q_{p(T)}}{\pi k} \ln R/A_e \quad \text{(flow to line of wells)}$$

$$h^2 - h_c^2 = \frac{Q_{p(T)}}{\pi k} \ln \frac{R}{A_e} \quad \text{(flow from line of wells to wellpoints, } R = A_e \text{ for well, i.e., } R = 230 \text{ ft)}$$

Equate h^2 and solve for $Q_{p(T)}$

$$H^2 - h_c^2 = \frac{nQ_w + Q_{p(T)}}{\pi k} \ln \frac{R}{A_e} + \frac{Q_{p(T)}}{\pi k} \ln \frac{R}{A_e}$$

In order to prevent excessive drawdown at the wells, with both wells and wellpoints operating, reduce Q_w by 50 percent. Then Q_w = 0.50(37.4) = 18.7 cfm.

$$(55)^2 - (8)^2 = \frac{8(18.7) + Q_{p(T)}}{0.1\pi} \ln \frac{3170}{230} + \frac{Q_{p(T)}}{0.1\pi} \ln \frac{230}{140}$$

$$Q_{p(T)} = 172 \text{ cfm} = 1287 \text{ gpm}$$

The flow per foot of header is

$$Q_p = \frac{Q_{p(T)}}{\text{length}} = \frac{1287}{4(220)} = 1.46 \text{ gpm/ft}$$

Assume a wellpoint spacing (a) of 8 ft. Thus the flow per wellpoint, Q_w , is: Q_w = 8(1.46) = 11.7 gpm = 1.56 cfm

Compute head at wellpoint, h_w , from eq 1 (fig. 4-22) ($h_e = h_p$)

$$h_c^2 - h_w^2 = \frac{Q_w}{\pi k} \ln \frac{a}{2\pi r_w}$$

$$(8)^2 - h_w^2 = \frac{1.56}{0.1\pi} \ln \frac{8}{2\pi(0.5)}$$

$$h_w = 7.7 \text{ ft}$$

For Q_w = 11.7 gpm, the hydraulic head losses are as follows:

H_e = 0.1 ft, from fig. 4-25a, curve 5

H_s = 1.0 ft, from fig. 4-25b

$H_v + H_r$ = 0.4 ft, from fig. 4-25c

H_w = 1.4 ft

Thus $h_w - H_w$ = 7.7 - 1.4 = 6.3 ft

Therefore, the required effective vacuum at the header = el 25 - 6.3 = 18.7 ft. Since this is less than the available 20 ft, a wellpoint spacing of 8 ft with the header at el 25 and the top of the wellpoint screen at el 4 would be satisfactory. Calculate drawdown at well from eq 3 (fig. 4-13) and 1 (fig. 4-14).

$$H^2 - h_w^2 = \frac{Q_w}{\pi k}[n \ln R - \ln nr_w - (n-1) \ln A_e] + \frac{Q_{p(T)}}{\pi k} \ln \frac{R}{Ae}$$

$$(55)^2 - h_w^2 = \frac{18.7}{\pi 0.1}[8 \ln 3170 - \ln 8(1.0) - (8 - 1) \ln 230] + \frac{172}{\pi 0.1} \ln \frac{3180}{230}$$

$$h_w = 11.7 \text{ ft}$$

From fig. 4-24, estimate H_w 0.7 ft: $h_w - H_w$ = 11.7 - 0.7 = 11.0 ft.

In order to provide adequate pump submergence, set deep-well pump at el 3. (Since the actual drawdown in a well may be greater than the computed drawdown, it is generally advisable to set the pump intake not less than 7 to 10 ft below the computed drawdown in the well.)

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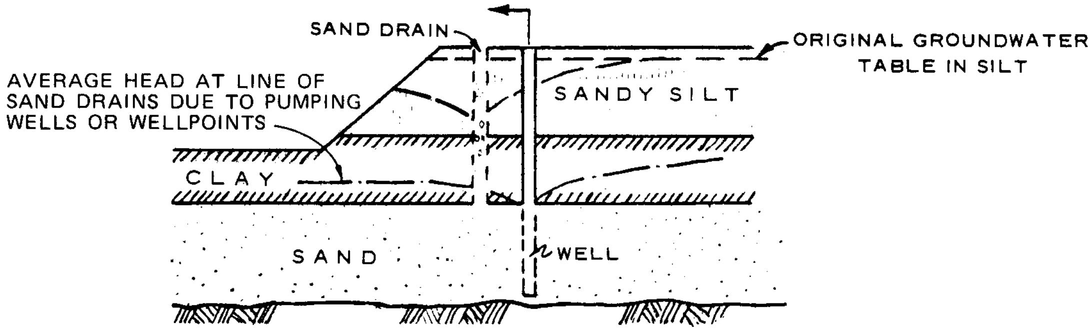
Figure D-4. Open excavation; combined deep-well and wellpoint system; gravity flow.



PROBLEM: Given a condition as shown, where $k = 5 \times 10^{-4}$ cm/sec, $H = 15$ ft, $z = 12$ ft, $z_1 = 3$ ft, $k_D = 1000 \times 10^{-4}$ cm/sec, $r_D = 0.5$ ft, $A_D = 0.785$ sq ft. Determine spacing of sand drains required to drain silt stratum.

SOLUTION: Compute Q_D from eq 4-12 assuming $h_w = 0$. Since Q_p must equal Q_D, substitute this value of Q_D in eq 1 (fig. 4-22) and compute h_o for various values of a assuming $h_w = 0$. Using these values of h_o and a, compute Q_p from eq 3 (fig. 4-3). The required spacing a is that which makes Q_p from eq 3 (fig. 4-3) equal to Q_D computed from eq 1 (fig. 4-22). From eq 4-12.

$$Q_D = \frac{0.20(12 - 3)0.785}{12} = 0.118 \text{ cfm} = 0.88 \text{ gpm}$$

Substituting this value of Q_D in eq 1 (fig. 4-22) and assuming $h_w = 0$ gives

$$h_o^2 = \frac{0.118}{\pi \times 0.001} \ln \frac{a}{2\pi(0.5)}$$

Also, from fig. 4-23, $L = 100$ ft for $H - h_w = 15$ ft. Substituting this value and the other constants into eq 3 (fig. 4-3) results in the following equation:

$$Q_p = \left[0.73 + \frac{0.27(15 - h_o)}{15}\right] \frac{0.001a}{2 \times 100}\left(15^2 - h_o^2\right)$$

Compute h_o and Q_p for various values of a from eq 1 (fig. 4-22) and eq 3 (fig. 4-3), respectively, which results in the values tabulated below.

a	h_o	Q_p	
ft	ft	cfm	gpm
5	4.17	0.045	0.34
10	6.58	0.086	0.65
15	7.65	0.117	0.88
20	8.33	0.143	1.07

From the tabulation above, the required spacing is 15 ft, since the corresponding value of $Q_p = Q_D$ computed from eq 4-12. However, since the above equations do not consider effect of entrance head loss, the drain spacing should be reduced somewhat. Therefore, a spacing of about 10 to 12 ft would be used.

EQUATIONS:

$$Q_D = K_D\, i\, A_D = \frac{k_D(z - z_1 + h_w)A_D}{z + h_w}$$

$$Q_p = \left(0.73 + 0.27\frac{H - h_o}{H}\right)\frac{ka}{2L}\left(H^2 - h_o^2\right)$$

$$h_o^2 = h_w^2 + \frac{Q_p}{\pi k} \ln \frac{a}{2\pi r_D} \quad \text{(where } h_D = h_d\text{)}$$

Note: To solve the equations above simultaneously, it is necessary to assume $h_w = 0$.

NOTATIONS:

Q_D = vertical flow per drain

Q_p = seepage through stratum being drained per length a measured along line of drains

k_D = vertical permeability of drain

A_D = sectional area of drain with radius r_D

k = permeability of stratum being drained

h_o = head at equivalent slot simulating line of drains

h_w = head at sand drain

a = spacing of drains

Other dimensions and symbols are as shown.

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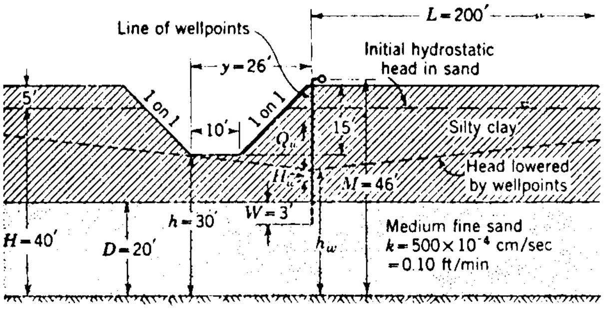
Figure D-5. Open excavation; pressure relief combined with sand drains; artesian and gravity flows.



PROBLEM: Determine required spacing of 2-1/2-in.-ID 0.35-in. long, style CB self-jetting wellpoints with 2-in.-ID riser pipes to lower hydrostatic head to bottom of trench. Assume effective vacuum at top of riser pipe = 20 ft, L = 200 ft, and r_w = 0.104 ft.

SOLUTION: Use a single line of wellpoints at top of excavation, one stage being required. For W/D = 3/20 = 0.15 , λ = 0.82 from fig. 4-4b; therefore λD = 0.82 X 20 = 16.4 ft. Maximum h at trench = 30 ft. Assume this value of h at the far edge of the trench, a distance y of 26 ft from the line of wellpoints. Compute the required h_o from eq 2 (fig. 4-4) as follows:

$$30 = h_e + (40 - h_e)\frac{26 + 16.4}{200 + 16.4} \text{ or } h_e = 27.7 \text{ ft}$$

The flow Q_p per unit length of system as computed from eq 1 (fig. 4-4) is

$$Q_p = \frac{2 \times 0.1 \times 20 \times 1 \times (40 - 27.6)}{200 + 16.4} = 0.23 \text{ cfm} = 1.7 \text{ gpm per ft of trench}$$

Compute Δh_w from eq 1 (fig. 4-20), h_w from eq 2 (fig. 4-21), and H_w from fig. 4-25, and select a so that $h_w - H_w \geqq 26$ ft (M minus the vacuum at the top of the riser pipe).

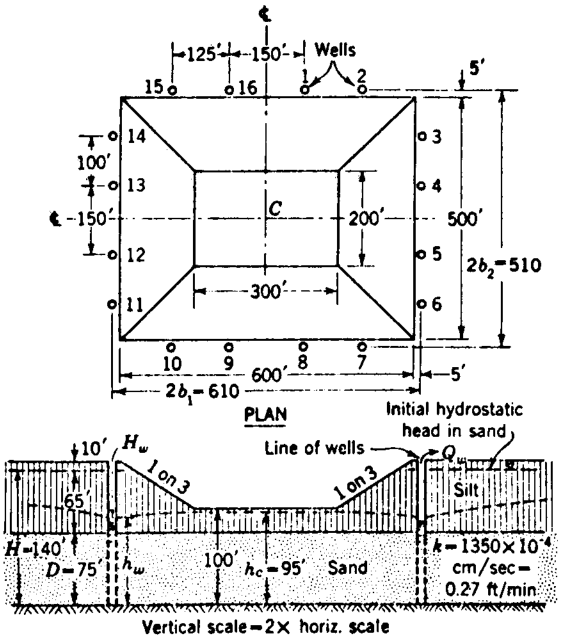
a ft	Q_w cfm	Δh_w ft	h_w ft	Head Loss in Wellpoint, ft: H_s†	H_e‡	$H_r + H_v$§	H_w	$h_w - H_w$ ft
10	2.3	0.50	27.2	1.75	0.22	0.87	2.84	24.4
8	1.8	0.36	27.3	1.16	0.17	0.54	1.87	25.4
6	1.4	0.25	27.5	0.74	0.13	0.34	1.21	26.3

† From fig. 4-25b.
‡ From fig. 4-25a, assuming H_e same as that given by curve 7.
§ From fig. 4-25c, assuming C = 110.

Thus a spacing of 6 ft would be required, since $h_w - H_w$ should not be less than 26 ft. The tops of the wellpoint screens would be set slightly below the top of the sand stratum.

(Modified from "Foundation Engineering," G. A. Leonards, ed., 1962, McGraw-Hill Book Company. Used with permission of McGraw-Hill Book Company.)

Figure D-6. Trench excavation; pressure relief by wellpoints; artesian flow.



SECTION

PROBLEM: Determine the number of 10-in.-diam wells with 6-in. gravel filter required to lower the head in the sand stratum 5 ft below bottom of excavation, for wells located at the top of slope and pumped by deep-well turbine pump (assume r_w = 1.0 ft). Use a fully penetrating system of wood-stave wells with 3/16-in. slots and a gravel filter with D_{10} size = 0.25 mm. Area of slot ≅ 10 percent of circumferential area of well screen. Geologic and soil conditions indicate a circular source of seepage k = 1,350 × 10^{-4} cm/sec or 2,700 × 10^{-4} fpm.

SOLUTION: Determine equivalent radius A_e of well system from eq 6 (fig. 4-14) with wells located 5 ft from crown of slope

$$A_e = \frac{4}{\pi}\sqrt{b_1 b_2} = \frac{4}{\pi} \quad \frac{610}{2} \times \frac{510}{2} = 355 \text{ ft}$$

From fig. 4-23, R ≅ 4,960 ft for k = 1,350 × 10^{-4} cm/sec and $H - h_w$ = 45 ft. Compute total required flow, Q_t, from eq IV-22 for h_w = 95 ft and $r_w = A_e$ = 355 ft.

$$Q_T = \frac{2\pi kD(H - h_w)}{\ln(R/r_w)} = \frac{2\pi(0.27)(75)(140 - 95)}{\ln 4{,}960/355} = 2{,}100 \text{ cfm} = 16{,}000 \text{ gpm}$$

As 1,000 gpm is about the maximum that can be pumped in a normal 10-in.-deep well pump, 16 wells would be required. Try spacing shown on plan. Make computations for the 4 wells in one quadrant and multiply the results by 4.

For 4 wells: drawdown at center of excavation $H - h_c$ is determined from eq 1 and 2 (fig. 4-10) ($R_i = R$): $Q_{wi} = \frac{15{,}000}{16}$ = 1000 gpm = 134 cfm

Well	R, ft	r_i, ft	$\ln\frac{R}{r_i}$
1	4,700	266	2.93
2	4,700	324	2.73
3	4,700	352	2.65
4	4,700	314	2.76
			Σ = 11.07

$$H - h_c = \frac{\sum_{m=1}^{m=4} Q_{wi} \ln \frac{R_i}{r_i}}{2\pi KD} = \frac{134(11.07)}{2\pi(0.27)(75)} = \mathbf{11.6 \text{ ft}}$$

For 16 wells:

$$H - h_c = 4(11.6) = 46.4 \text{ ft}$$

or

$$h_c = 140 - 46.4 = 93.6 \text{ ft}$$

Since the maximum allowable h_c is 95 ft, the system shown in plan is adequate. The approximate head h_w at a well is computed from eq 1 (fig. 4-20) using an average well spacing, a, of 2(510 + 610)/16 = 140 ft.

$$\Delta h_w = \frac{Q_w}{2\pi kD} \ln \frac{a}{2\pi r_w} = \frac{134}{2\pi(0.27)75} \ln \frac{140}{2\pi(1.0)} = 3.3 \text{ ft; or } h_w \cong 93.6 - 3.3 = 90.3 \text{ ft}$$

Hydraulic head losses in wells are obtained from fig. 4-24, assuming intake of pump is about 85 ft above the bottom of the sand.

H_e = 0.60 ft (from fig. 4-24a, with Q_w = 1,000 gpm/75 ft of screen = 13.3 gpm/ft
H_s = 0.37 ft (from fig. 4-24b using a screen length of 0.5(75) = 37.5 ft)
H_r = 0.07 ft (from fig. 4-24b, for 10 ft of riser pipe and C = 130)
H_v = 0.26 ft (from fig. 4-24c)
H_w = 1.30 ft

Thus the water surface in the wells would be about 90.3 - 1.3 = 89.0 ft above the bottom of sand. Set pump bowl about 85 ft above bottom of sand and provide with 10-ft suction pipe.

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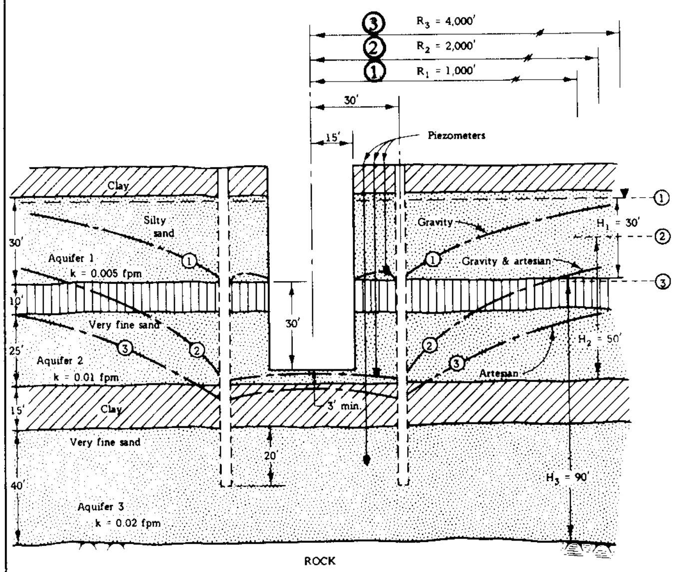
Figure D-7. Rectangular excavation; pressure relief by deep wells; artesian flow.



PROBLEM: Design a deep well and vacuum system to dewater a 70-ft deep shaft to be sunk into stratified clays and sand below the groundwater table. Assume a ring of wells installed 15 ft out from perimeter of shaft with an equivalent radius of influence, A, = 30 ft. Wells to fully penetrate the sand strata penetrated by the shaft and pumps to have a capacity in excess of the flow to each well. Vacuum to be maintained in wells equals 15 ft. Assume radius of influence of vacuum (R) to be the same for seepage (i.e., vacuum varies from that at well or wells to zero at R). Maximum height of shaft exposed at any one time equals 30 ft.

SOLUTION:

Aquifer 1. Compute flow of water to wells assuming gravity flow for hydrostatic head, and "equivalent" artesian flow for the additional head produced by the vacuum in the wells. Assume h_w = 2 ft. Hydrostatic water flow, from eq 2 (fig. 4-11) (r_w = A):

$$Q_{T\text{-}H\text{-}1} = \frac{\pi k(H^2 - h_w^2)}{\ln R/A} = \frac{0.005\pi(30^2 - 2^2)}{\ln 1000/30} = 4.01 \text{ cfm}$$

Vacuum water flow, from eq 2 (fig. 4-10) (r_w = A; effective aquifer thickness, $D = \frac{H + h_w}{2}$; and drawdown, $H - h_w$, = V):

$$Q_{T\text{-}V\text{-}1} = \frac{2\pi k\left(\frac{H + h_w}{2}\right)V}{\ln R/A} = \frac{2(0.005)\pi\left(\frac{30 + 2}{2}\right)(15)}{\ln 1000/30} = 2.15 \text{ cfm}$$

Total water flow, aquifer 1, $Q_{T\text{-}1} = Q_{T\text{-}H\text{-}1} + Q_{T\text{-}V\text{-}1} = 4.01 + 2.15 = 6.16$ cfm = 46.1 gpm.

Aquifer 2. Compute the flow of water assuming combined artesian-gravity flow conditions for "Hydrostatic" water flow. Compute the additional flow caused by vacuum in wells assuming an equivalent artesian flow condition under the net vacuum head existing in the gravity flow region. Assume h_w = 2 ft.

Hydrostatic water flow, from eq 1 (fig. 4-12):

$$Q_{T\text{-}H\text{-}2} = \frac{\pi k(2DH - D^2 - h_w^2)}{\ln R/A} = \frac{0.01\pi[2(25)(50) - (25)^2 - (2)^2]}{\ln 2000/30} = 14.0 \text{ cfm}$$

Vacuum water flow; compute $\bar{R}$ from eq 3 (fig. 4-12)

$$\ln \bar{R} = \frac{(D^2 - h_w^2)\ln R + 2D(H - D)\ln A}{2DH - D^2 - h_w^2} = \frac{(25^2 - 2^2)\ln 2000 + 2(25)(50 - 25)\ln 30}{2(25)(50) - (25)^2 - (2)^2} = 4.80$$

then $\bar{R}$ = 121 ft.

Estimate vacuum at artesian-gravity flow boundary by plotting the vacuum versus log r (V = 15 ft at A = 30 ft; V = 0 at R = 2,000 ft), the vacuum is 10 ft at R = 121 ft. Thus the net vacuum in the gravity flow region = 15 ft - 10 ft = 5 ft. Vacuum water flow, from eq 2 (fig. 4-10)

$$Q_{T\text{-}V\text{-}2} = \frac{2\pi k\left(\frac{D + h_w}{2}\right)V}{\ln R/A} = \frac{2(0.01)\pi\left(\frac{25 + 2}{2}\right)5}{\ln 121/30} = 3.04 \text{ cfm}$$

Total water flow, aquifer 2, $Q_{T\text{-}2} = Q_{T\text{-}V\text{-}2} + Q_{T\text{-}H\text{-}2} = 14.0 + 3.04 =$ 17.04 cfm = 127.5 gpm.

Aquifer 3. For artesian flow, the head producing flow for the combined hydrostatic-vacuum system is $H + V - h_e$. Assuming the circular array of wells to be a continuous drainage slot, for which W/D = 50 percent and R/A = 133, it can be seen from fig. 4-7 that the head in the center of the circular drainage slot approaches the head in the slot as R/A increases. Therefore, the flow to the wells for this situation can be computed from eq 2 (fig. 4-10), in which $(H - h_w) = (H + V - h_e)$, G = 1, and r_w = A.

$$Q_T = \frac{2\pi kD(H + V - h_e)}{\ln R/A} = \frac{2(0.02)\pi(40)(90 + 15 - 27)}{\ln 4000/30} = 80.1 \text{ cfm} = 599 \text{ gpm}$$

Total flow to well system = 46.1 + 127.5 + 599.4 = 773 gpm.

Use 12 wells located 30 ft from the center of the shaft, with a spacing (a) between wells of 15.5 ft.

$$\text{Flow per well, } Q_w = \frac{773}{12} = 64,4 \text{ gpm} = 8.61 \text{ cfm}$$

Compute Δh_w for the artesian flow in aquifer 3 to determine the required drawdown in the well. From eq IV-80 (and fig. IV-21 for values of θ_a),

$$\Delta h_w = \frac{Q_w \theta_a}{kD} = \frac{64 \times 0.5}{7.5 \times 0.02 \times 40} = 5.33 \text{ ft}$$

Thus h_w = 57 - 5.3 = 51.7.

Use 8-in. well screens with 6-in.-thick filter surrounding the screen. Check screen hydraulics:

	Aquifer 1	Aquifer 2	Aquifer 3
Total flow	46.1 gpm	127.5 gpm	599.4 gpm
Well flow, Q_w	3.8 gpm	10.6 gpm	50.0 gpm
Wetted screen length	2.0 ft	2.0 ft	20.0 ft
Flow per ft of screen	1.9 gpm	5.3 gpm	2.5 gpm

From fig. 4-24a, it can be seen that the well entrance losses (H_e) should be negligible.

Vacuum system. It is assumed that the overlying clay is a continuous impermeable formation, and that the quantity of air that may enter the aquifers through the clay is negligible compared to that which will enter through the exposed excavation surface. It is also assumed that only one aquifer will be exposed at a time, and that the permeability of the aquifers for the flow of air is effectively reduced by half due to the capillary water retained in the voids of soil following the lowering of the water table.

Compute the airflow to the wells from eq 1 (fig. 4-3). To obtain the shape factor, construct a plan flow net for the flow of air from the shaft excavation to the wells, for which

$$\mathcal{S} = \frac{N_f}{N_e} \quad 0.6 \text{ per well}$$

$$Q_a = \Delta p(D - h_w)\frac{\mu_w}{\mu_a}$$

Aquifer 1

$$Q_a = 15 \text{ ft}(30 \text{ ft} - 2 \text{ ft})\frac{0.005}{2}\left(\frac{2.359 \times 10^{-5} \text{ lb-sec/ft}^2}{3.744 \times 10^{-7} \text{ lb-sec/ft}^2}\right)0.6 = 39.7 \text{ cfm/well}$$

Total airflow = 12(39.7) = 47.6 cfm at the mean absolute pressure,

$\bar{p}$, of $\frac{34 + (34 - 15)}{2}$ = 26.5 ft of water.

Compute the required vacuum pump capacity

$$Q_{a\text{-}vp} = Q_a\frac{\bar{p}}{34} = 476\left(\frac{26.5}{34}\right) = 371 \text{ cfm}$$

Aquifer 2

$$Q_a = 15(25 - 2)\frac{0.01}{2}\left(\frac{2.359 \times 10^{-5}}{3.744 \times 10^{-7}}\right)0.6 = 65.2 \text{ cfm/well}$$

Total airflow = 12(65.2) = 783 cfm at p = 26.5 ft of water

$$Q_{a\text{-}vp} = 783\left(\frac{26.5}{34}\right) = 610 \text{ cfm}$$

Provide vacuum pumps with a total capacity of 610 cfm at 15 ft (of water) vacuum.

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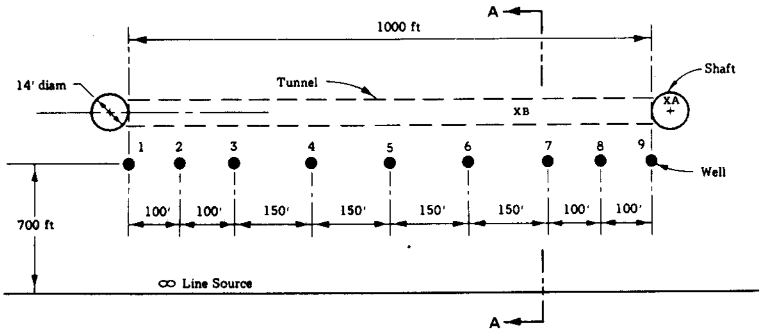
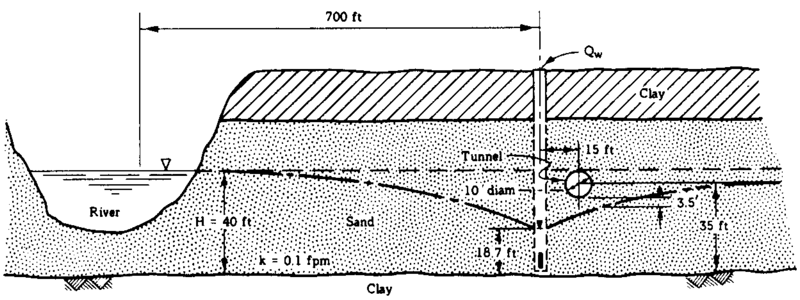
Figure D-8. Shaft excavation; artesian and gravity flows through stratified foundation; deep-well vacuum system.

PROBLEM: Design a deep-well system to dewater an excavation for a tunnel for the conditions shown. For a single-line source, use the method of image analysis. The layout, as shown, was determined from an approximate flow net sketched for preliminary design purposes.



PLAN



SECTION A-A

SOLUTION: Assume 12-in. fully penetrating wells with surrounding filter, r_w = 1.0 ft. For an assumed Q_w = 150 gpm, the drawdown at points A and B and at well 5 are computed from eq 2 and 3 (fig. 4-18):

$$H^2 - h_p^2 = \frac{1}{\pi k} \sum_{i=1}^{i=n} Q_{wi} \ln \frac{S_i}{r_i}$$

	At Point A			At Point B			At Well 5		
Well	r_i ft	S_i ft	ln S_i/r_i	r_i ft	S_i ft	ln S_i/r_i	r_i ft	S_i ft	ln S_i/r_i
1	1010	1740	0.54	730	1590	0.78	500	1490	1.09
2	910	1680	0.61	630	1540	0.89	400	1455	1.29
3	810	1630	0.70	530	1510	1.05	300	1430	1.56
4	660	1560	0.86	380	1465	1.35	150	1410	2.24
5	510	1500	1.08	230	1430	1.83	1	1400	7.24
6	360	1460	1.40	80	1415	2.87	150	1410	2.24
7	210	1430	1.92	80	1415	2.87	300	1430	1.56
8	110	1420	2.56	175	1425	2.10	400	1455	1.29
9	17	1415	4.42	275	1440	1.66	500	1490	1.09
Total			14.09			15.40			19.60

$h_p^2 = 1600 - \frac{150\ (14.09)}{0.1\pi(7.5)}$ $\qquad$ $h_p^2 = 1600 - \frac{150\ (15.40)}{0.1\pi(7.5)}$ $\qquad$ $h_p^2 = h_w^2 = 1600 - \frac{150\ (19.60)}{0.1\pi(7.5)}$

h_p = 26.5 ft $\qquad$ h_p = 24.9 ft $\qquad$ h_w = 18.8 ft,

For h_w = 18.8 ft, the flow per foot of well screen would be $\frac{150 \text{ gpm}}{18.8}$ = 8.0 gpm/ft, which is a satisfactory rate of inflow. The maximum allowable head at points A and B is 35 - 5 - 3.5 = 26.5. Thus the system is adequate.

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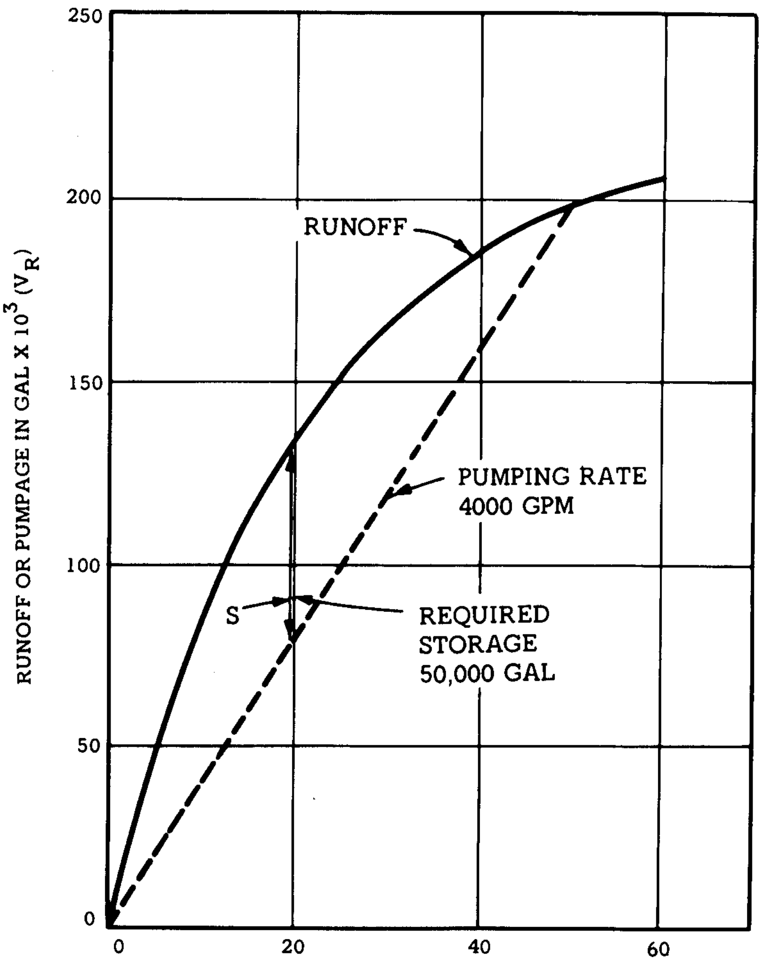
Figure D-9. Tunnel dewatering; gravity flows; deep-well system.



PROBLEM: Determine sump and pump capacity to control surface water in an excavation, 4 acres in area, located in Little Rock, Ark., for a rainstorm frequency of 1 in 5 years and assuming c = 0.9. Assume all runoff to one sump in bottom of excavation.

SOLUTION:

$$V_R = cRA$$

FROM FIGURE:

Rainstorm, min	R, in.	V_R - (X 10^3 gal)
10	0.85	83
30	1.70	166
60	2.10	205

Assume sump pump capacity = 4000 gpm. From plot, required storage = 50,000 gal.

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Figure D-10. Sump and pump capacity for surface runoff to an excavation.